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Several oxygen injection systems have been investigated to enhance the dissolved oxygen distribution in the withdrawal zone of a reservoir, thereby increasing the dissolved oxygen concentration in the downstream area. Additionally, oxygen injection could result in nitrogen stripping in the water column as a result of the induced changes in the relative partial pressures.

A short-term field study was conducted to investigate the effect of

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oxygen injection on dissolved nitrogen concentrations. An innovative portable gas chromatograph system was used to measure dissolved nitrogen and the results were compared with data obtained from simpler, but less accurate systems. In the immediate vicinity of the oxygen-injection site, the nitrogen released far overshadowed the nitrogen stripped and a net increase was observed. The maximum nitrogen concentration observed in the reservoir was 111 percent of surface saturation. The increase in nitrogen concentration was apparently due to denitrification of entrained anoxic sediments.

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Preface

During 14 July 1977 and 23-24 August 1977, dissolved nitrogen measurements were made at Clarks Hill Reservoir, Georgia-South Carolina, by the Hydraulics Laboratory (HL) of the U. S. Army Engineer Waterways Experiment Station (WES) to evaluate the effect of oxygen injection on concentrations of dissolved nitrogen in the reservoir. This effort was under the Environmental and Water Quality Operational Studies (EWQOS) (Task IIIB) sponsored by the Office, Chief of Engineers, and under the purview of the Environmental Laboratory (EL), WES, and was supported by Work Unit 31605, entitled "Evaluate the Effectiveness of Reservoir Aeration/Oxygenation Techniques."

The study reported herein was conducted under the direction of Messrs. H. B. Simmons, Chief, HL, and John L. Grace, Jr., Chief of the Hydraulic Structures Division and Reservoir Water Quality Branch (Physical), HL. Dr. John Harrison was Chief, EL. Program Manager of EWQOS was Dr. Jerome L. Mahloch, EL, WES. Personnel participating in the tests were Messrs. David H. Merritt, Bruce Murray, and Charles H. Tate, Jr., of WES and Dr. Daniel Leggett of the U. S. Army Engineer Cold Regions Research and Engineering Laboratory. This report was prepared by Messrs. Merritt and Leggett and reviewed by Mr. Grace.

The Commanders and Directors of WES during this study and the preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Fred R. Brown.

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DISSOLVED NITROGEN MEASUREMENTS AT CLARKS HILL RESERVOIR, GEORGIA-SOUTH CAROLINA

Background

1. Temperate lakes and reservoirs typically stratify during the late spring and summer months, and anaerobic or low dissolved oxygen conditions may develop in the hypolimnion. Since many reservoirs have fixed level outlets located in the middepths or deeper, the release water quality may be poor and adversely impact the downstream area.

2. Structural add-ons that permit withdrawal of well oxygenated epilimnetic waters may be used to alleviate this condition. Provisions to completely destratify the reservoir or induce localized mixing that forces the epilimnetic water down to the level of the outlet may be used for relatively small shallow lakes to increase the dissolved oxygen (D.O.) in the release. These techniques usually result in an increase in the temperature of the water released. When it is also desired that a project meet coldwater temperature objectives downstream, these alternatives may not be feasible and an alternative method may be needed to oxygenate the hypolimnetic waters. This is particularly needed when the desired withdrawal zone from the lake or reservoir is beneath the metalimnion and higher levels of withdrawal will result in temperatures greater than desired.

3. Oxygenation or aeration of the hypolimnion is normally achieved by pumping oxygen or air below the metalimnion. Pumping air has been reported to be less expensive than oxygenation but it requires that a large amount of air be pumped, since air is only 21 percent oxygen. This is difficult to do without at least a significant amount of localized destratification. Pumping air also has the disadvantage of inducing high concentrations of dissolved nitrogen. Fast and Lorenzen (1976) observed concentrations of N_2 as great as 167 percent relative to the surface. Nitrogen supersaturation in the tailwaters may result in fish kills from gas embolism. Although currently considered costly, oxygen

injection may be a viable alternative for reservoirs with deep releases low in D.O. when a coldwater fishery is to be maintained downstream.

Project Description

4. Clarks Hill Reservoir is a 3,577,000,000 m^3 reservoir located on the Savannah River and the Georgia-South Carolina border (Figures 1 and 2), and is operated by the Savannah District (SAS) of the South Atlantic Division (SAD), U. S. Army Corps of Engineers. The reservoir is 42.7 m deep at the dam, and the penstocks are located approximately 21.3 m below the water surface. During summer stratification, D.O. levels in the tailwaters usually fall to or below 3 mg/l. The Georgia Department of Natural Resources has classified the waters below Clarks Hill Dam as drinking waters, requiring a daily average D.O. concentration of 5 ppm with no concentration less than 4 ppm at all times and a water temperature not greater than 32.2°C. Similarly, the South Carolina Department of Health and Environmental Control has classified the river below Clarks Hill Dam as Class B, also requiring a daily D.O. concentration no less than 5 ppm with a minimum of 4 ppm and a water temperature not greater than 32.2°C.

5. SAS contracted with Dr. Richard Speece of Drexel University to develop and test an oxygenation system in Clarks Hill Reservoir. If effective, a similar system could be used on the Proposed Richard B. Russell Reservoir to meet environmental objectives. The reach below Richard B. Russell Dam was designated as a trout stream by the Georgia Department of Natural Resources, requiring a daily average D.O. concentration of 6 ppm with no less than 5 ppm at all times and coldwater temperatures (generally less than 21.1°C). During three summers of field testing at Clarks Hill Reservoir, Speece (1975, 1977) investigated a number of different diffuser types, loading rates, and locations. A "pulsed" injection system was developed which could raise the D.O. content of power releases to the desired levels; however, it has a high capital cost. The purpose of the 1977 study was to determine if a system providing a continuous, lower rate of injection and located 1.8 km

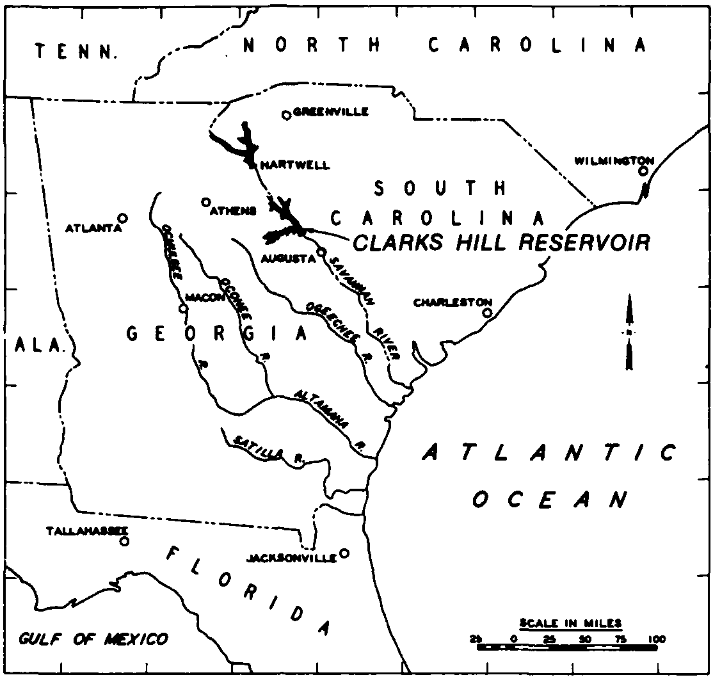

Figure 1. Vicinity map

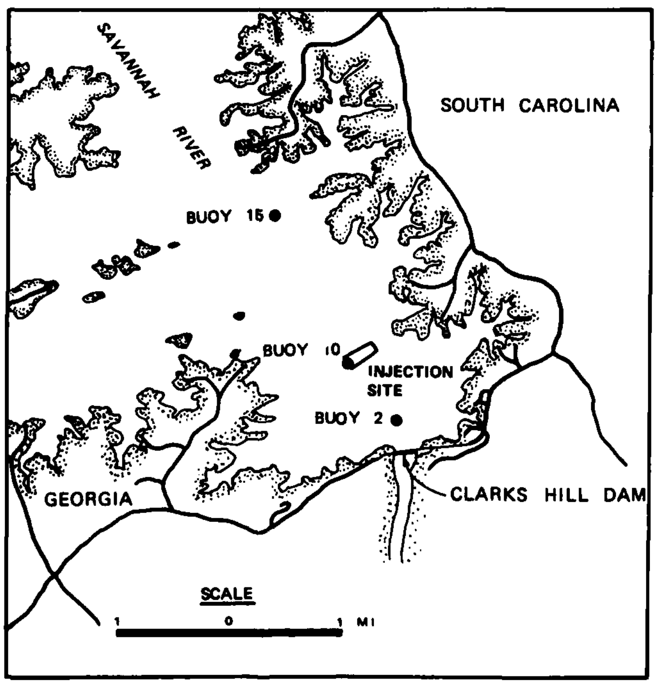

Figure 2. Injection and sampling sites, 1977, Clarks Hill Reservoir

upstream of the powerhouse could obtain the same objective.

Scope and Purpose of Study

6. The purposes of this study were: (a) to obtain background data on dissolved nitrogen levels, and (b) to determine what effect oxygen injection has on dissolved nitrogen concentrations. Specifically, it was thought that oxygen injection might cause nitrogen stripping. A short-term field study was designed to accomplish these objectives.

7. Dissolved nitrogen is difficult to measure in the field, and is usually calculated from measurements of the total dissolved gases. The Cold Regions Research and Engineering Laboratory, which has experience in using a portable gas chromatograph to measure dissolved nitrogen, collaborated in this effort. Profiles were taken before and three weeks after the oxygenation system was started.

Equipment

8. Gas chromatograph. Samples were taken at various depths with a van Dorn sampler, and subsequently the subsample was transferred without agitation to a 50-ml gas-tight syringe (Hamilton). Dissolved gases were extracted by equilibration with ultra-pure helium (99.995) using the technique of McAuliffe (1971). An aliquot of the headgas was then injected via a 1-ml gas sampling loop into an AID Model 512 gas chromatograph (Figure 3). The chromatograph was equipped with a 1.8 m column of Molecular Sieve 5-A, 80-100 mesh (Analabs) and a thermal conductivity detector operated at ambient temperature. This technique is sufficient to separate oxygen from nitrogen, but not from argon.

9. The detector response to these gases was determined by injection of 50-100 ml of atmospheric air. A preliminary study confirmed that detector response was directly proportional to concentration; therefore, the concentration in the samples could be calculated using the standard composition of atmospheric air (excluding water vapor). Correction of the oxygen data for dissolved argon was done using the volume

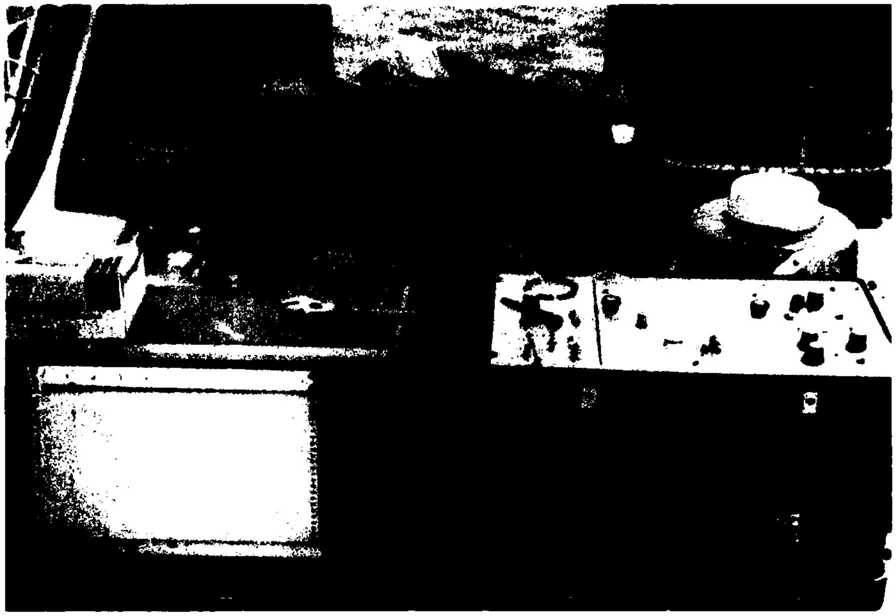

Figure 3. Gas chromatograph system

ratio of Ar/N_2 of 0.024. Analyses of laboratory distilled water indicated the precision of the method (standard deviation) was 2.5 percent for O_2 and 1.3 percent for N_2, respectively. The average values from these determinations were 5.84 and 10.82 ml (at standard temperature and pressure) which agreed well with values of 5.86 and 10.83 calculated from the solubility data of Klots and Benson (1963). In general, good agreement was found between the field measurements made with the gas chromatograph, Hydrolab Surveyor, and Winkler titration.

10. Hydrolab Surveyor. Temperature, D.O., pH, conductivity, and redox were measured as a function of depth using a Hydrolab Surveyor system (Figure 4). The D.O. probe was calibrated using the Azide modification of the Winkler titration technique. Initially, measurements were made at the surface, at 1-m intervals from 5 to 15 m of depth, and at 5-m intervals between 15 and 40 m (bottom); subsequently, measurements were taken every 1 m.

Tests and Results

11. On 14 July 1977, complete profiles were taken at two locations:

Figure 4. Hydrolab Surveyor

(a) Buoy 10, which was near the planned injection site, and (b) Buoy 15, which was approximately 1 mile upstream of the oxygen injection site (Figure 2). This provided an initial test of the gas chromatograph system and background data regarding dissolved nitrogen concentrations. The D.O. measurements made with the Hydrolab system agreed very well with those made using the gas chromatograph (Plate 1). The assumption was made that if the D.O. measurements made using the gas chromatograph agreed with an independent determination of the oxygen profile, then the dissolved nitrogen measurements would also be valid. (This validation was necessary because the use of a portable gas chromatograph to measure dissolved gases in this manner was a novel technique.)

12. Plate 2 shows the dissolved nitrogen concentrations observed during July at Buoys 10 and 15. Nitrogen saturation relative to the surface is shown also, as a reference.

13. With the exception of the values at the 1-m depth for Buoy 10, and at the 20-m depth for Buoy 15, all of the nitrogen concentrations were slightly below saturation--approximately 95 $\pm$ 5 percent of

saturation at the surface. The supersaturation seen at the 20-m depth at Buoy 15 is probably an erroneous measurement, and the supersaturation observed at the 1-m depth for Buoy 10 may be due to fluctuations in the saturation concentration caused by diurnal heating and cooling.

14. The results indicate that the background dissolved nitrogen concentrations are temperature-dependent and that the concentrations were approximately 90 to 100 percent of saturation at the surface of the reservoir.

15. On 23 and 24 August 1977, profiles were again taken at Buoy 10, Buoy 15, and Buoy 2 (located near the dam). The oxygenation system had been operating for approximately three weeks. Again, the correlation between D.O. measured with the gas chromatograph and that measured with the Hydrolab Surveyor showed a high degree of consistency (Plate 3). It may also be seen (Plates 4 and 5) that the greatest amount of oxygenation occurred in the epilimnion and upper metalimnion. The reservoir had also warmed appreciably during this period (Plate 6), primarily in the hypolimnion, which increased the percent nitrogen saturation of the hypolimnetic waters relative to that at the surface of the reservoir.

16. Very little difference was noted between the July and August dissolved nitrogen profiles taken at Buoy 15, located approximately one mile upstream of the injection site (Plate 7). However, a marked change was noted between the July and August profiles taken at Buoy 10, which was in the immediate vicinity of the injection system (Plate 8). The dissolved nitrogen level at the injection site was higher during August than in July. The level was also significantly higher than the dissolved nitrogen level at either Buoy 15 or Buoy 2 (Plate 9). Dissolved nitrogen levels at Buoys 2 and 15 ranged from 89 to 104 percent of saturation; whereas, the levels measured at Buoy 10 were between 102 and 111 percent of saturation, relative to the surface.

17. The increase in dissolved nitrogen in the near field was totally unexpected, since laboratory tests have shown that nitrogen

stripping takes place during oxygenation.* However, Dudley (1978) measured decreased redox potential and increased conductivity in the near field during oxygen injection. He postulated that this was the result of the entrainment of sediments into the rising water-oxygen plume. The resultant combination of entrained anoxic sediments with oxygenation would cause denitrification of sediments and the release of molecular nitrogen. This mechanism is also supported by field experiments reported by Tiren (1976). Depending upon operating conditions, the release of molecular nitrogen by denitrification of entrained sediments could overshadow nitrogen stripping.

Conclusions

18. The scheme and rate of oxygen injection replenished the oxygen in the metalimnion and epilimnion of Clarks Hill Reservoir and enhanced the D.O. levels in the hypolimnion by 2 or 3 mg/l. Although the released D.O. was outside the scope of this study, it should be noted that Speece (1977) reported that D.O. concentration in the turbine discharge averaged 4.6 mg/l with fluctuations up to 6 mg/l, depending on the turbine discharge pattern.

19. The increase is dissolved nitrogen due to oxygen injection was only observed at the injection site; however, this is not presumptive evidence that it did not exist elsewhere in the forebay. Other changes in lake chemistry, as reported by Dudley (1978) and attributed to the injection scheme, were observed in the vicinity of Buoy 2. In the immediate vicinity of the injection site, the nitrogen released far overshadowed the nitrogen stripped, and a net increase was observed. The maximum N_2 concentration observed in the reservoir was 111 percent of surface saturation. Nitrogen concentration could probably be reduced by increasing the spacing between the diffusers and/or reducing the injection rate per diffuser to prevent sediment entrainment.

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* Personal communication, S. Vigander, Tennessee Valley Authority, Norris, Tenn.

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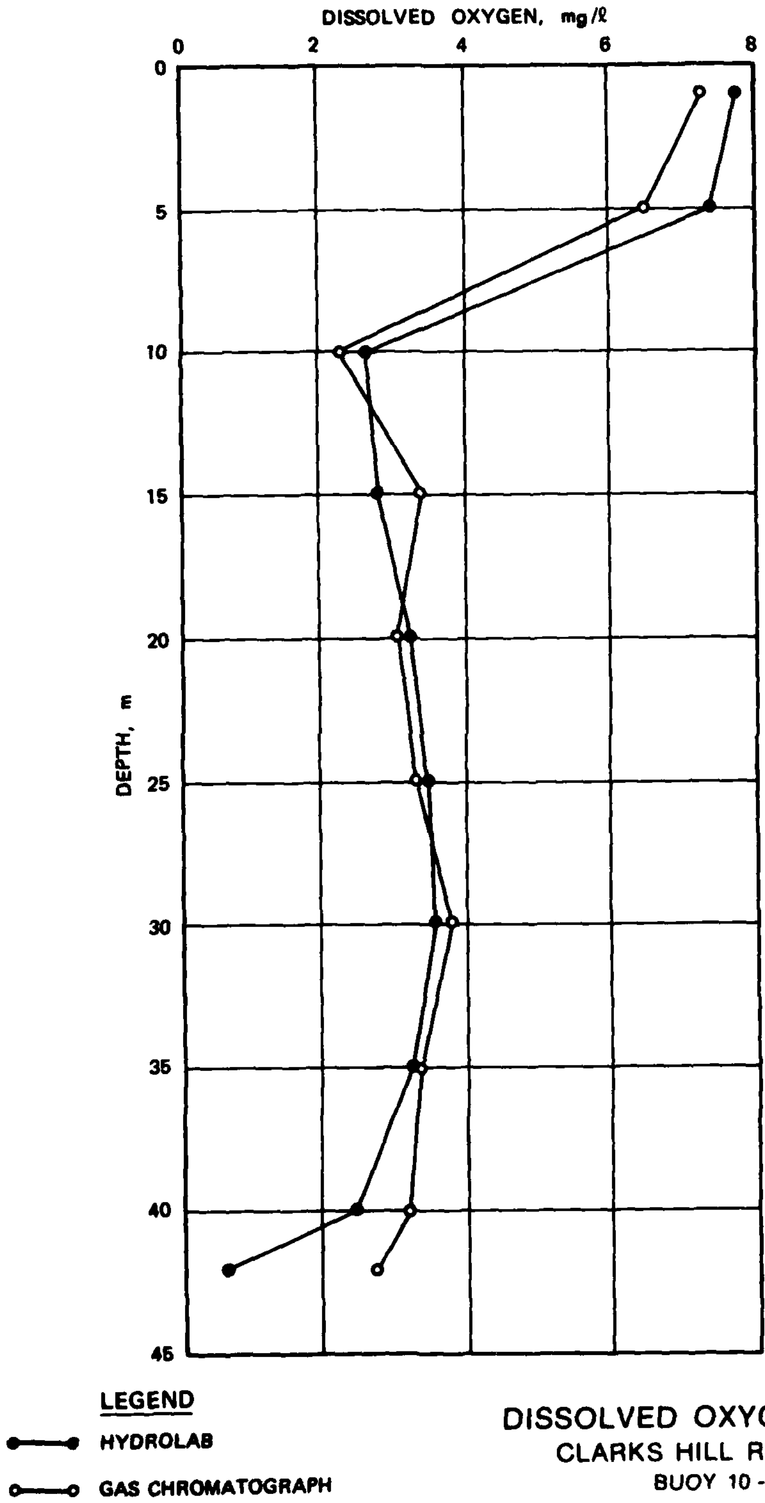
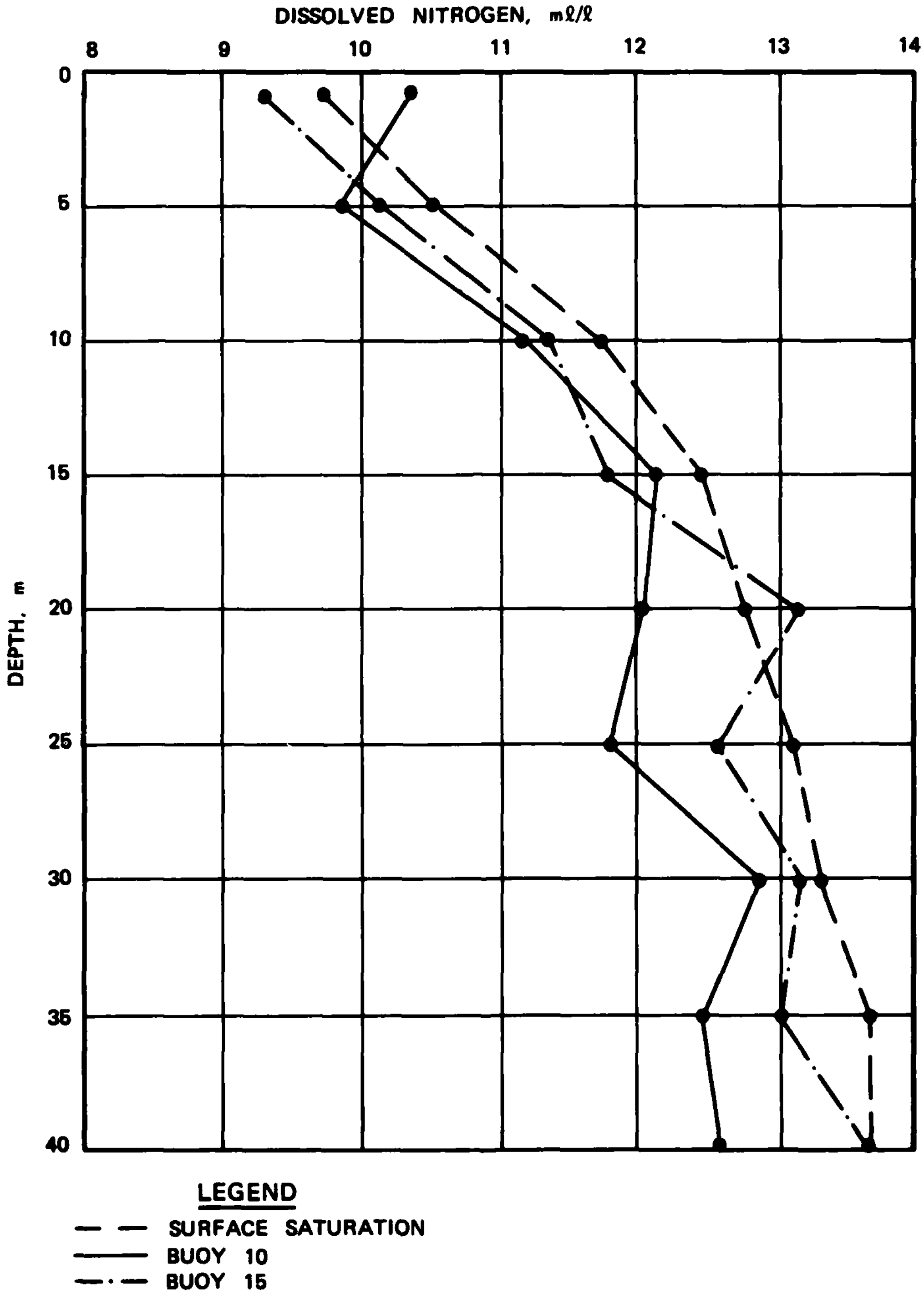


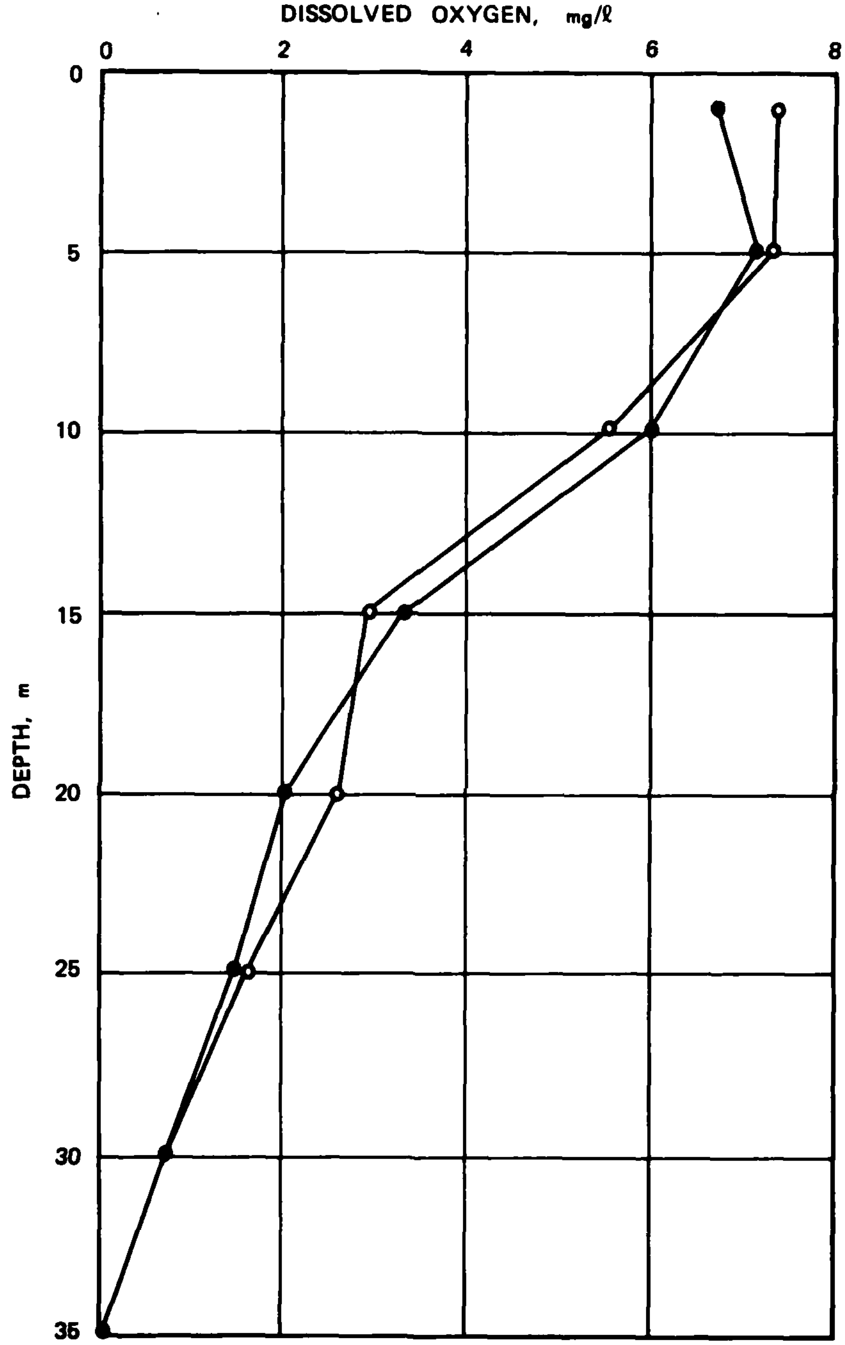
DISSOLVED OXYGEN PROFILE
CLARKS HILL RESERVOIR
BUOY 10 - 1977

PLATE 1



DISSOLVED NITROGEN PROFILE
CLARKS HILL RESERVOIR
BUOY 10,15 - 1977

PLATE 2



LEGEND

●——● GAS CHROMATOGRAPH

○——○ HYDROLAB

DISSOLVED OXYGEN PROFILE

CLARKS HILL RESERVOIR

BUOY 15 - AUGUST 1977

PLATE 3

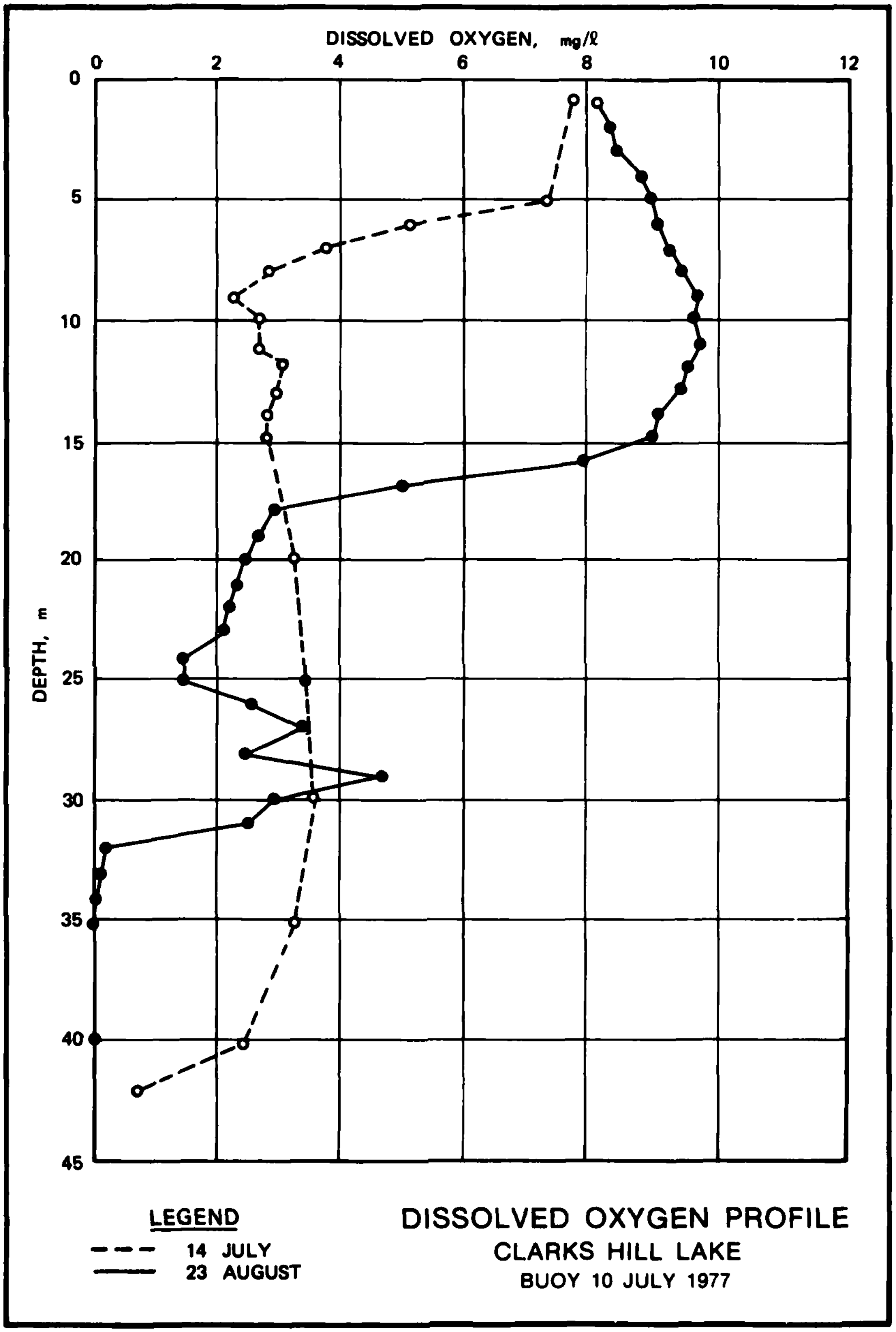
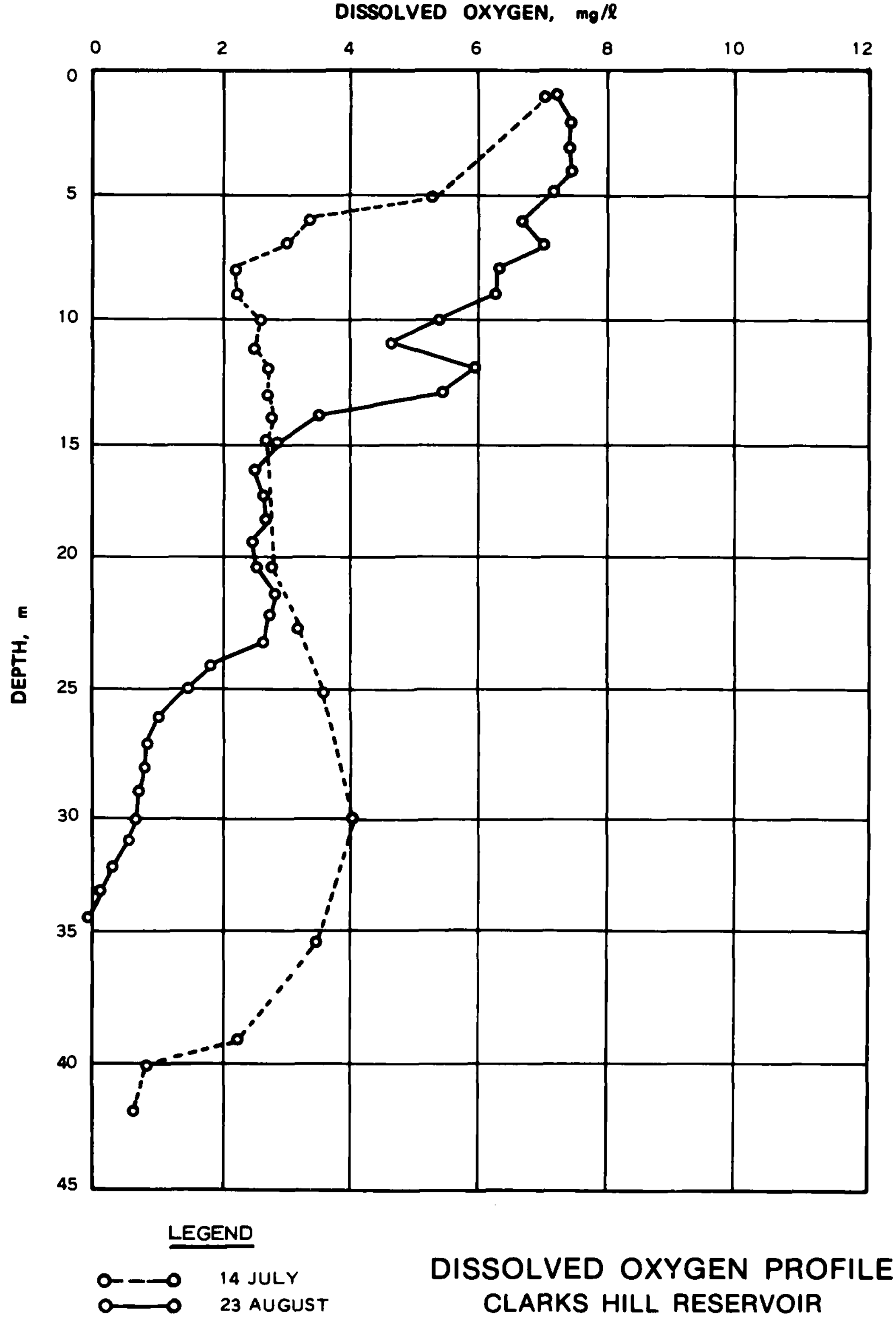
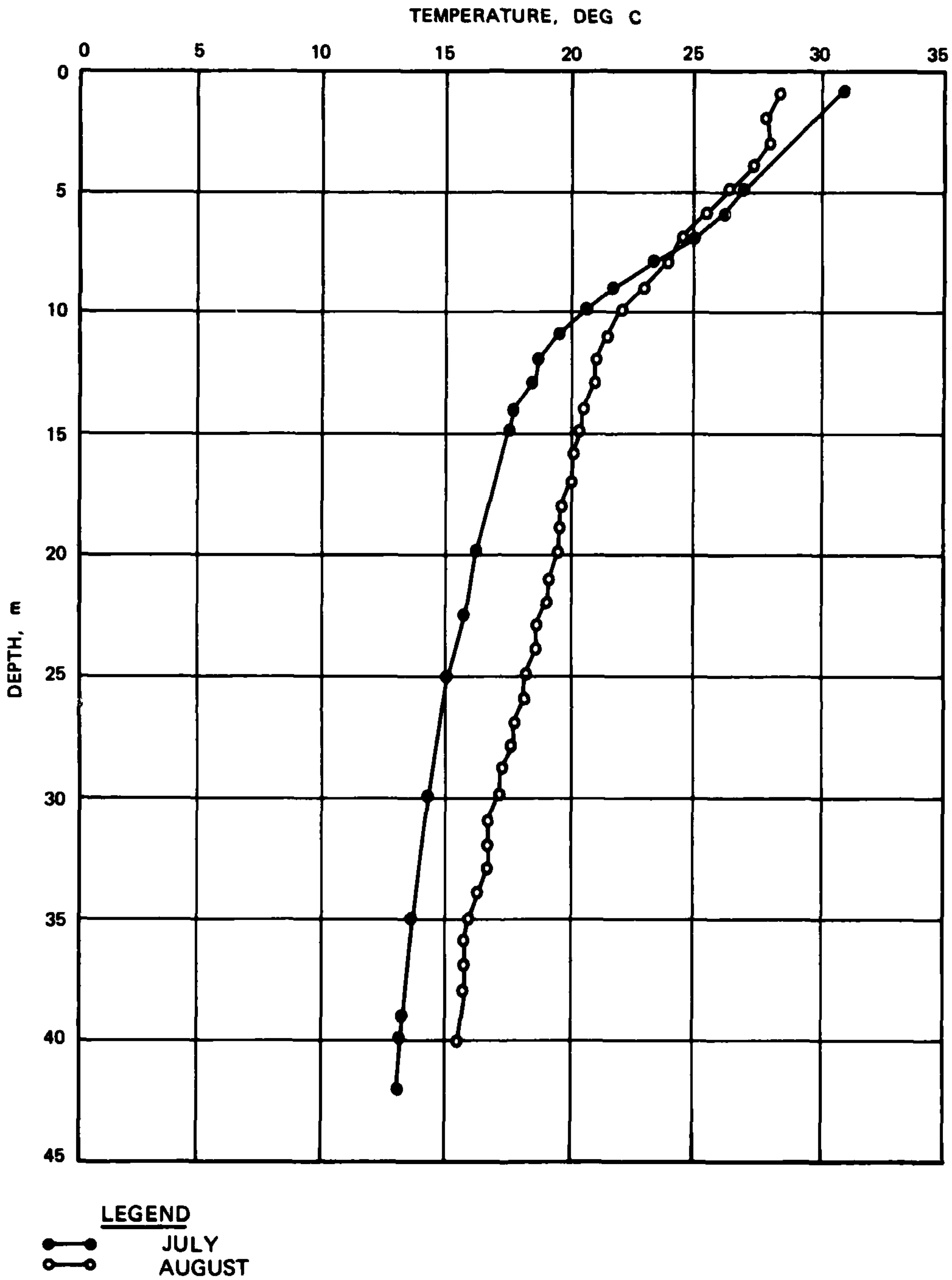

DISSOLVED OXYGEN, mg/ℓ
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
45
DEPTH, m
LEGEND
14 JULY
23 AUGUST
DISSOLVED OXYGEN PROFILE
CLARKS HILL LAKE
BUOY 10 JULY 1977

PLATE 4



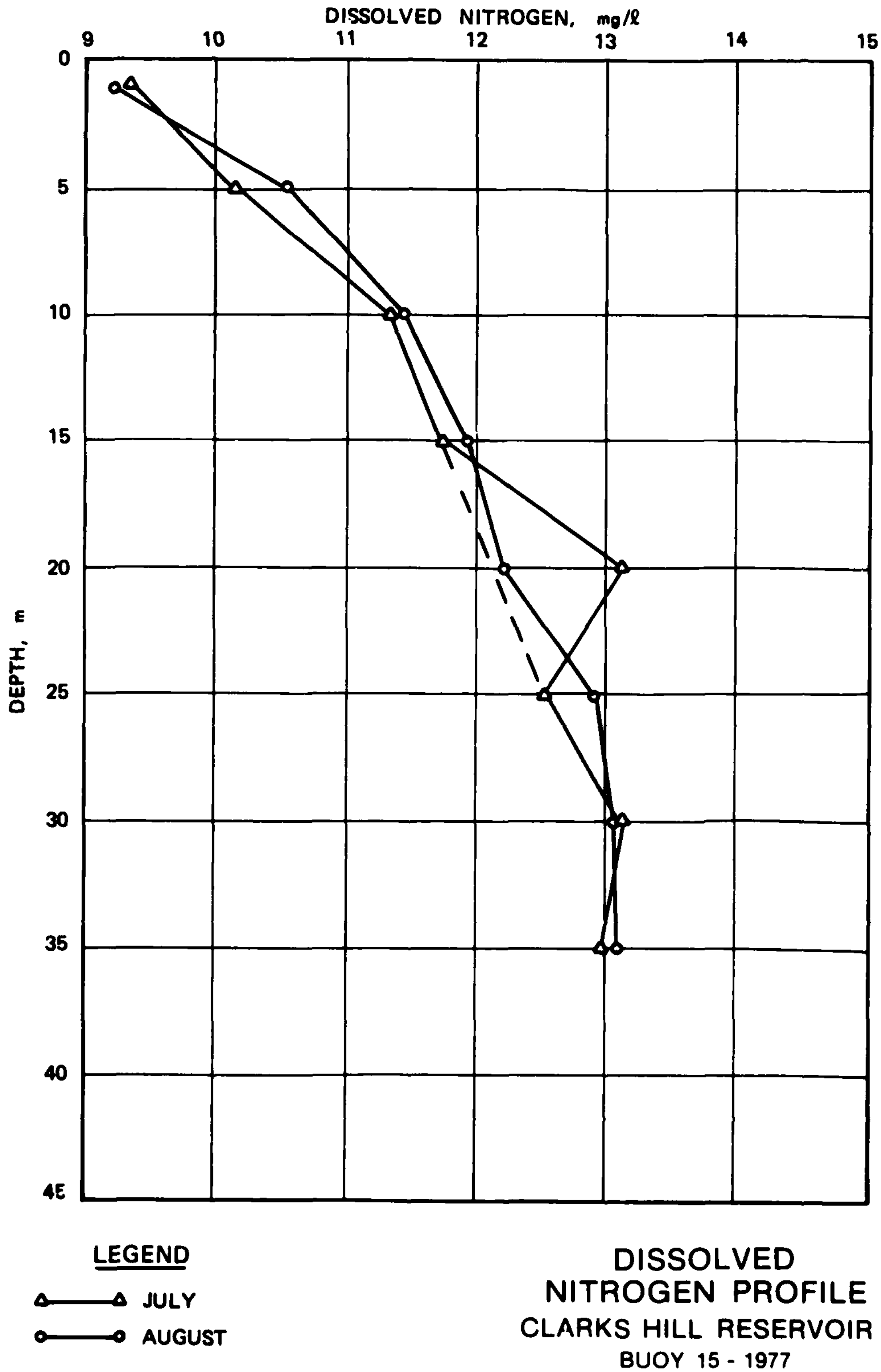
DISSOLVED OXYGEN PROFILE
CLARKS HILL RESERVOIR
BUOY 15 - 1977

PLATE 5



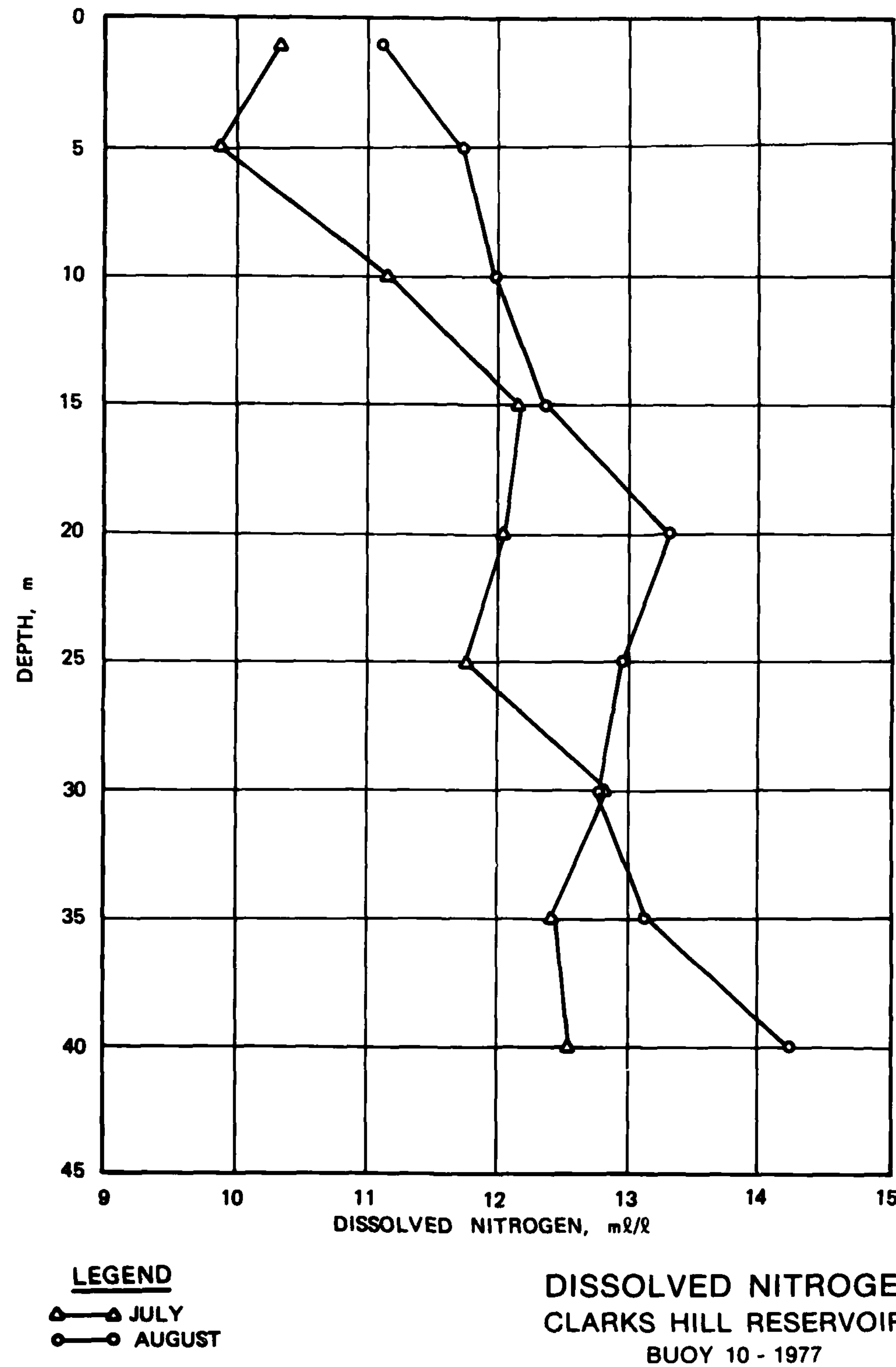
TEMPERATURE, °C
CLARKS HILL RESERVOIR
BUOY 15 - 1977

PLATE 6

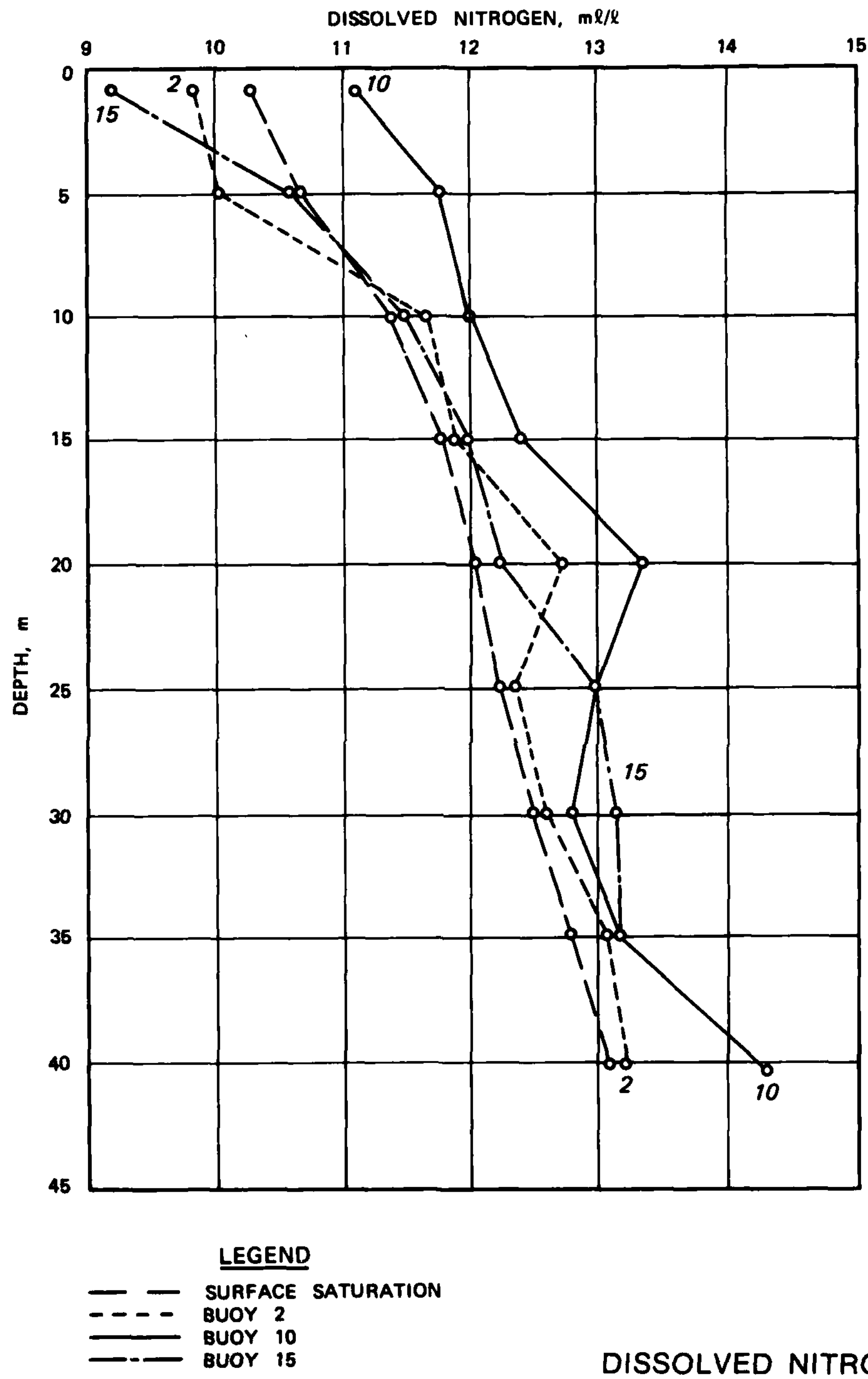


DISSOLVED
NITROGEN PROFILE
CLARKS HILL RESERVOIR
BUOY 15 - 1977

PLATE 7



DISSOLVED NITROGEN
CLARKS HILL RESERVOIR
BUOY 10 - 1977



DISSOLVED NITROGEN
CLARKS HILL RESERVOIR
BUOY 2, 10, 15 - 1977

PLATE 9

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1. Gas chromatography. 2. Nitrogen supersaturation. 3. Reservoirs. 4. Water--Dissolved oxygen. I. Leggett, Daniel. II. Cold Regions Research and Engineering Laboratory (U.S.) III. United States. Army. Corps of Engineers. Office of the Chief of Engineers. IV. Environmental and Water Quality Operational Studies. V. U.S. Army Engineer Waterways Experiment Station. Environmental Laboratory. VI. Title VII. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; E-81-3.
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